Spacecraft Navigation Using X-ray Pulsars

Suneel I. Sheikh
(ASTER Labs, Inc.)
&
Demetrios Matsakis
(U.S. Naval Observatory)

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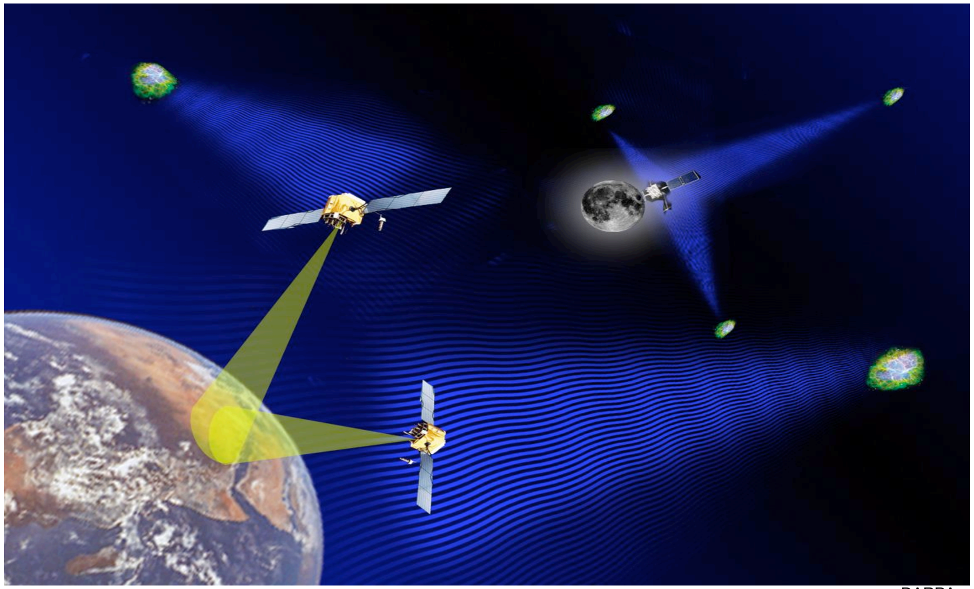
XNAV Program Description

- Provide a *GPS-free*, autonomous spacecraft navigation capability
- Develop navigation capability exploiting celestial X-ray sources for time, position, velocity, and attitude determination
  - **Develop high fidelity catalog of candidate sources.**
  - **Develop new X-ray sensors to meet stringent imaging and timing requirements.**
  - **Develop advanced navigation algorithms incorporating X-ray photon time of arrival data.**
- New system capable of operating in various orbits
  - LEO, HEO, GEO, Cis-lunar, Interplanetary



DARPA

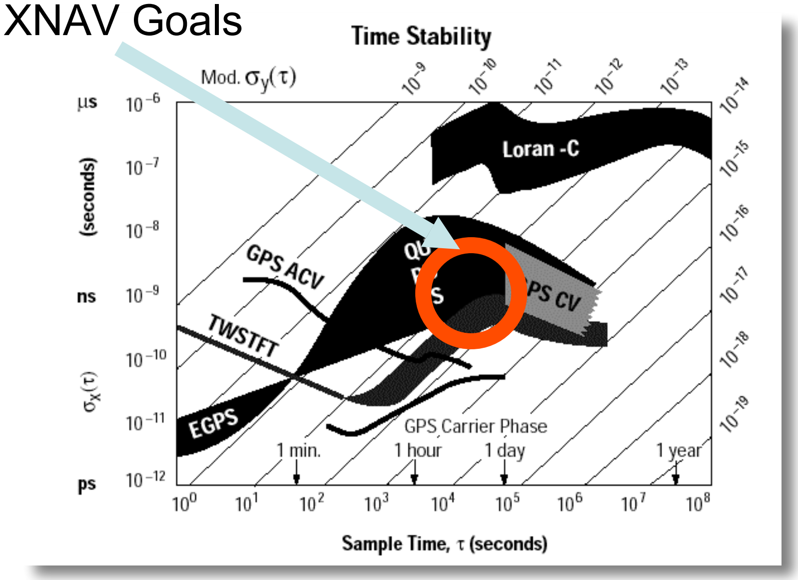
Notional XNAV Concept

XNAV is a U.S. DARPA led program with cooperation from NASA

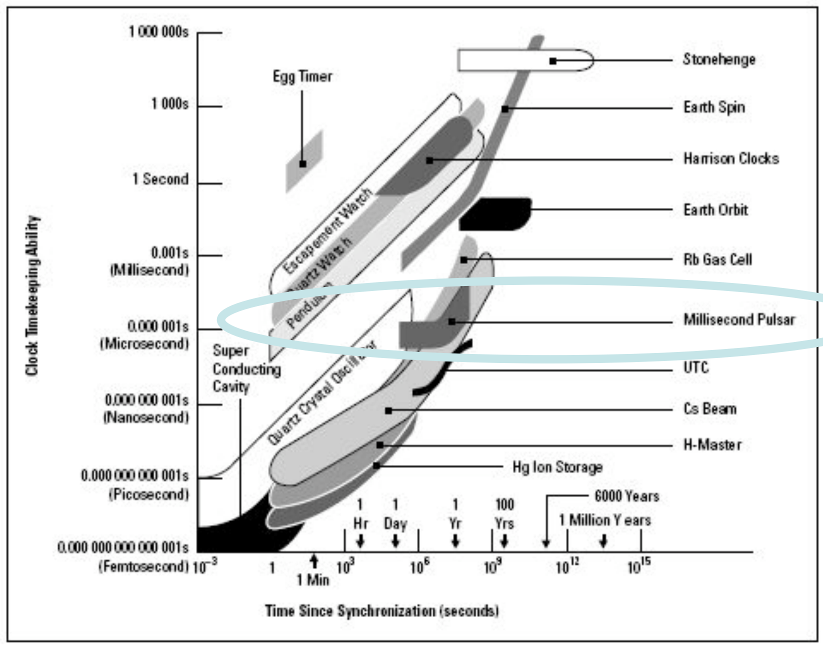
XNAV Program Goals

- Autonomously determining spacecraft position and time requires high fidelity system
  - **Photon time tagging resolution < 1 μs.**
  - **Large area, gimbaled detectors.**
  - **Accurate navigation algorithms, incorporating existing pulse timing models and relativistic time transfer**

XNAV Goals



Allan, Ashby & Hodge, 1997

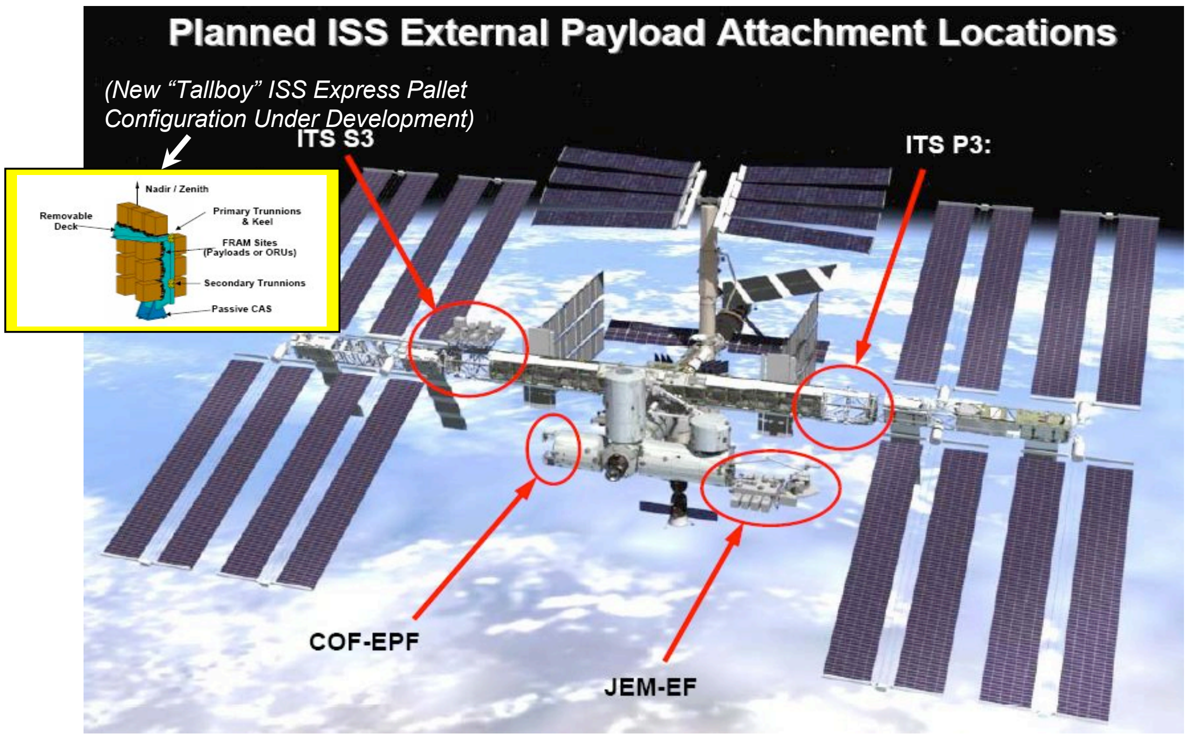


Stable sources with short periods

Allan, Ashby & Hodge, 1997

XNAV System Testing

- Plan is to use Space Shuttle to deploy test system to ISS (2009)
  - Provided adequate test environment without cost of supporting vehicle
    - Express Logistics Carrier (ELC)
  - Eventually test on free-flyer mission
- Test and verification system integrated into experiment design
- Science data from X-ray sources will be provided to community

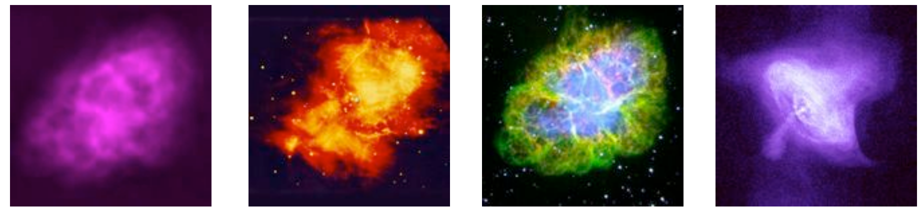


DARPA

X-ray Sources

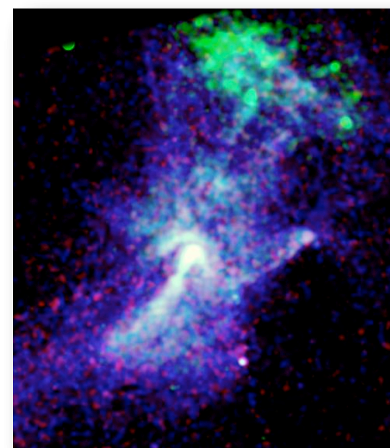
- Benefits
  - Many variable sources
  - Unique signatures
  - Wide coverage in sky
  - Small detectors for spacecraft
    - 5000 cm^2 detector area

Observations of Crab Nebula and Pulsar at Various Wavelengths



Radio (VLA/NRAO) | **Infrared** (2MASS/UMass/ IPAC-Caltech/NASA/NSF) | **Visible** (Palomar Obs.) | **X-ray** (NASA/CXC/SAO)

- Issues for Navigation
  - Few “bright” sources
    - Low energy flux
    - Requires long observation times
  - Source characteristics
    - Transient (on/off for unknown duration)
    - Flares and Bursts (high intensity signal brief duration)
    - Glitches (star-quakes)
  - X-ray experimentation requires on-orbit testing

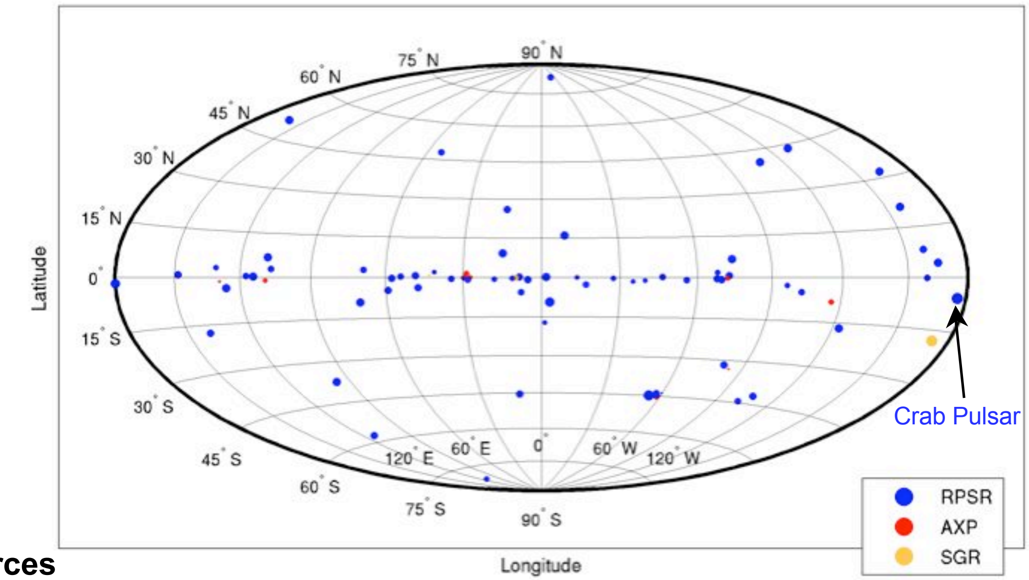


Pulsar B1509-58
(Chandra X-ray Observatory
NASA/MIT/B.Gaensler et al.)

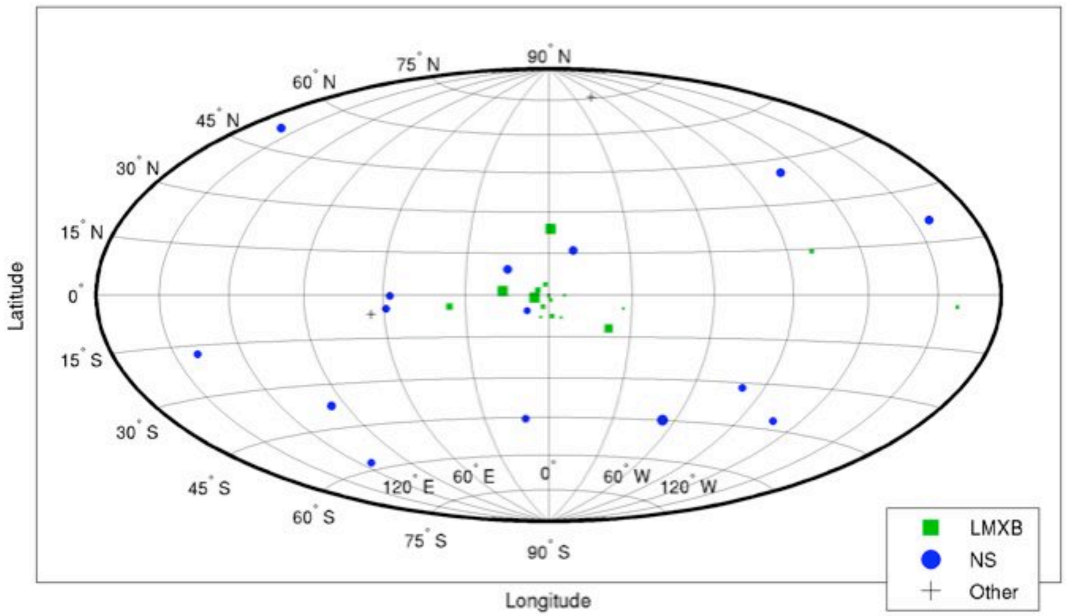
X-ray Source Location Plots

- Isolated neutron stars

Galactic Latitude and Longitude of Neutron Stars



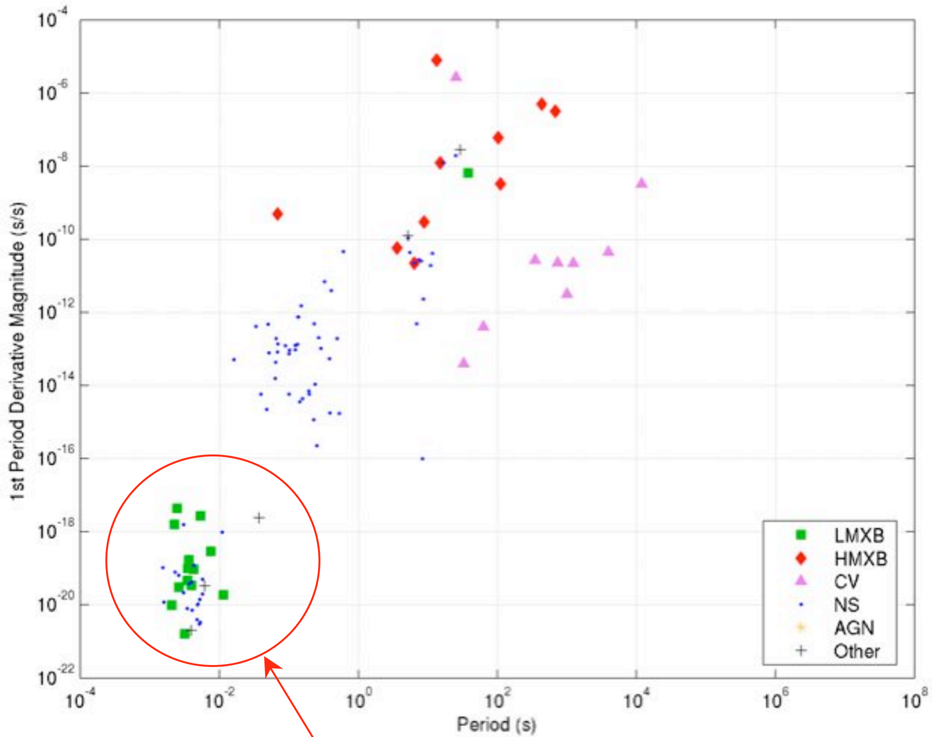
Galactic Latitude and Longitude of Millisecond Sources



- Millisecond sources (period < 0.02 seconds)

Source Characteristics Analysis

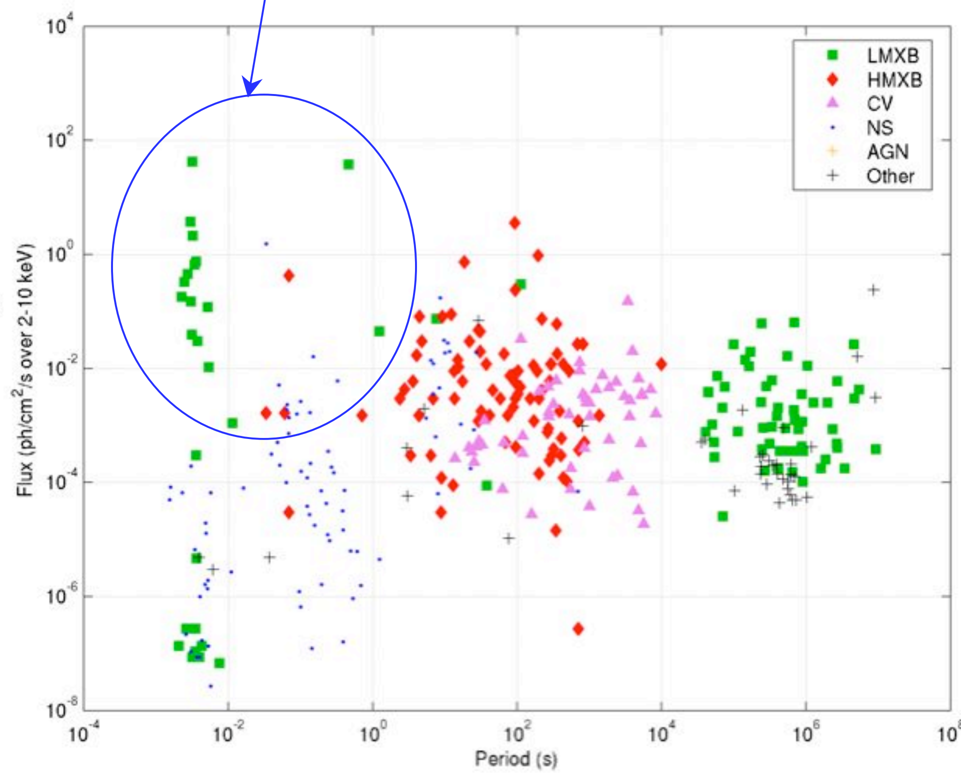
Period Derivative versus Period



– Short period objects also have small period derivatives

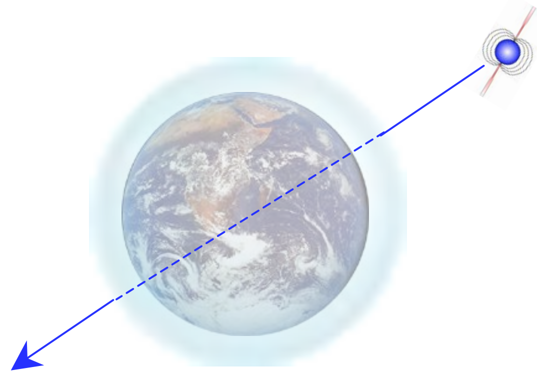
– Some short period objects have higher X-ray flux

X-ray Flux versus Period

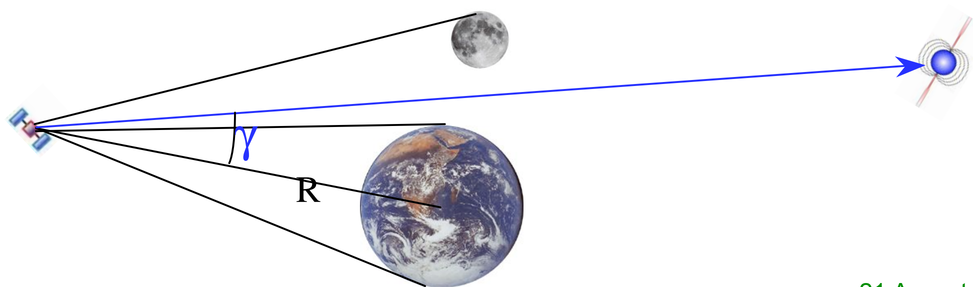


Conventional Position Methods

- Methods similar to visible stars
  - Occultation
    - Pass behind celestial body’s limb
      - ex. Earth
      - X-rays absorbed by atmosphere

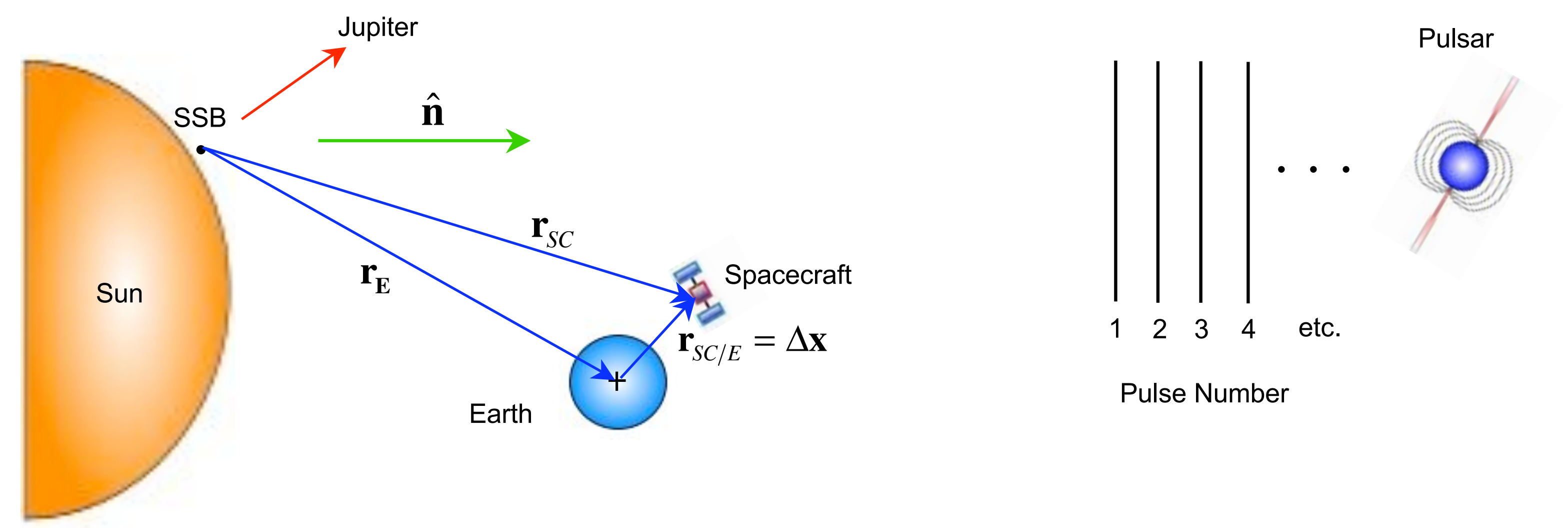


  - Pulsar Elevation
    - Compare direction to pulsar to known direction and distance of celestial body (ex. Earth, Moon)
    - Adjust distance to body via measured pulsar direction



Spacecraft Orbits

Time-Position Relationship



Time Transfer Equation: $t_{SSB} = t_{SC} + \dfrac{\hat{\mathbf{n}} \cdot \mathbf{r}_{SC}}{c} + O(\text{Relativistic Terms})$

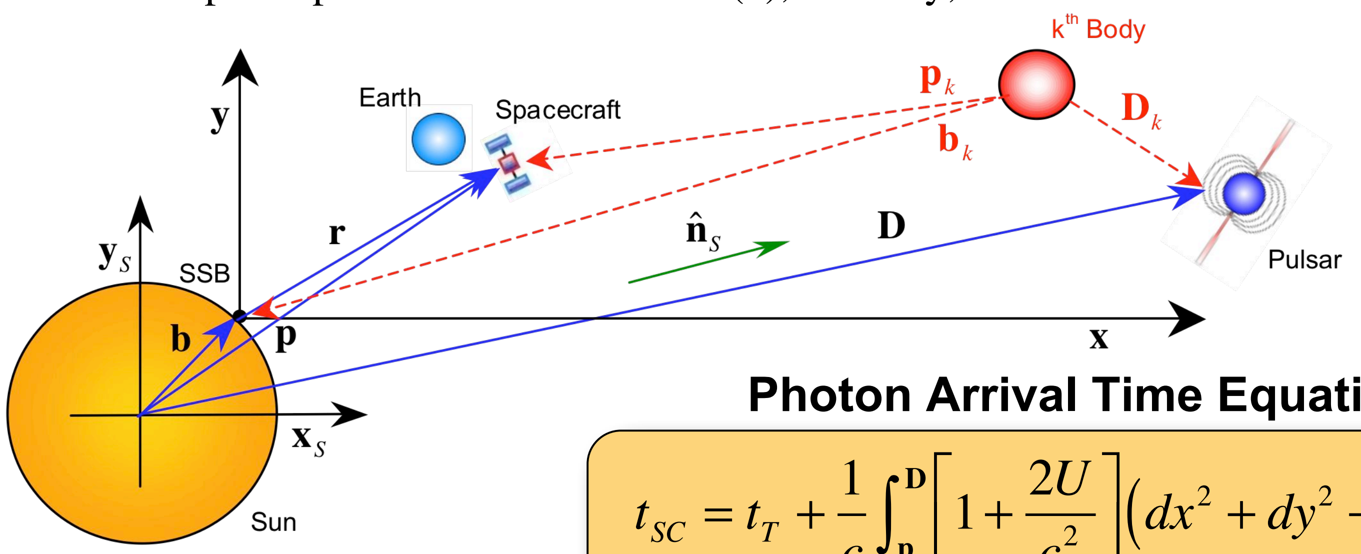
Pulsar Timing Model

$$\Phi(t) = \Phi(t_0) + f[t - t_0] + \frac{\dot{f}}{2}[t - t_0]^2 + \frac{\ddot{f}}{6}[t - t_0]^3$$

Φ is phase of cycle, t_0 is reference epoch, f is pulse frequency

Barycenter Time Transfer

- Photon transmitted from source and arrives at spacecraft detector
  - Photons follow null geodesics (paths) of light rays entering solar system
- Analytical expression to transfer time from any position in solar system into inertial frame with origin of solar system barycenter (SSB)
  - Photons follow null geodesics (paths) of light rays entering solar system
    - Example implementations: TEMPO (2), AXBary, SAXDAS



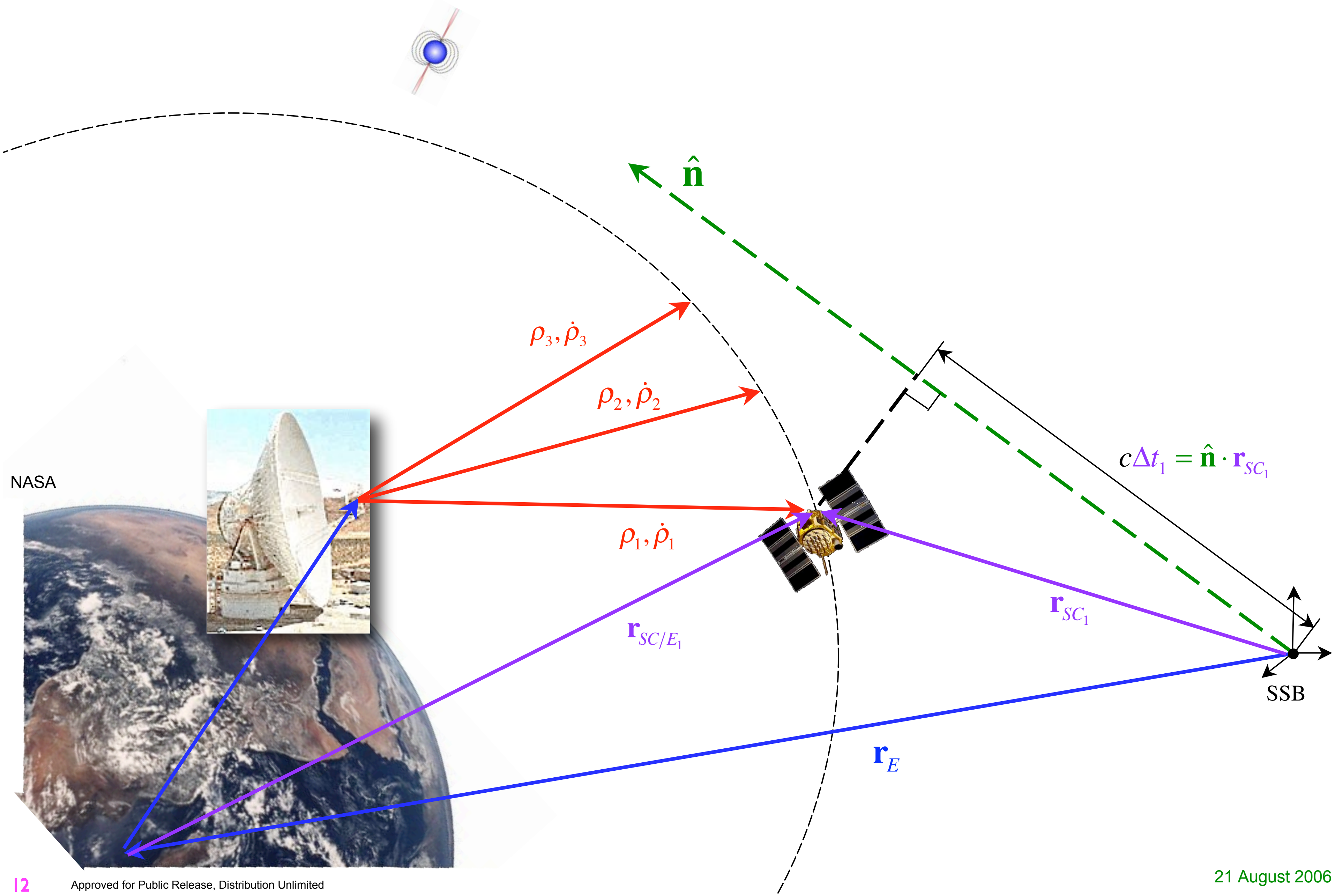
Photon Arrival Time Equation

$$t_{SC} = t_T + \frac{1}{c}\int_{\mathbf{p}}^{\mathbf{D}} \left[1 + \frac{2U}{c^2}\right]\left(dx^2 + dy^2 + dz^2\right)^{\frac{1}{2}} d\mathbf{x}$$

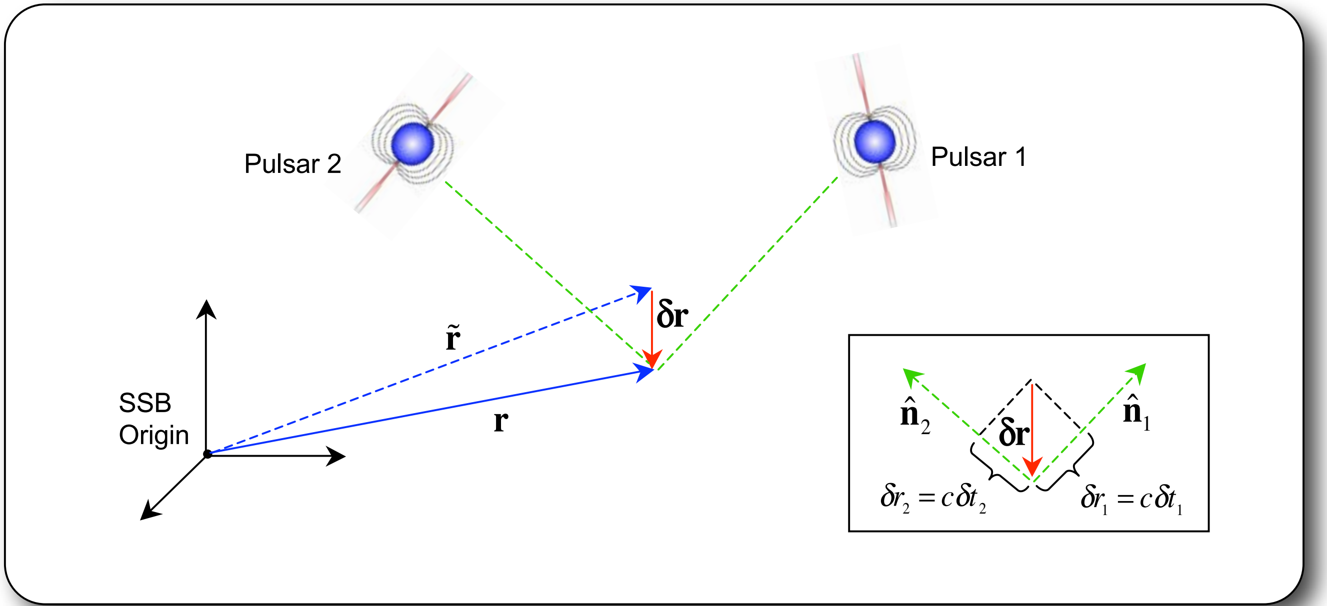
Time Transfer Equation

$$\left(t_{SSB} - t_T\right) - \left(t_{SC} - t_T\right) = \left(t_{SSB} - t_{SC}\right)$$

3-D Orbit Determination



Delta-Position Correction Method

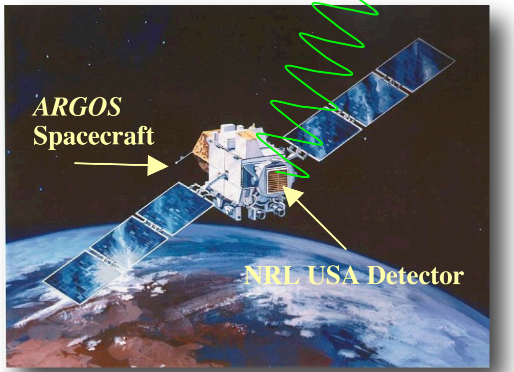


- Compare *measured* pulse TOA to *predicted* TOA
  - Use estimated position to compute measured TOA
  - Difference is delta position (position offset) along line of sight to pulsar
- Computes position relative to SSB
- Continually refine position estimate using multiple pulsar measurements

Delta-Correction Validation

- *ARGOS* Operations
  - 850 km orbit altitude, 98.7° inclination
- NRL USA Experiment Observations
  - Compute delta position estimates
  - Compare estimate to known position error

Crab Nebula and Pulsar
(NASA/CXC/ASU/J.Hester et al.)



Rockwell

- USA observations in December 1999

POSITION OFFSETS FROM CRAB PULSAR OBSERVATIONS BY USA DETECTOR.

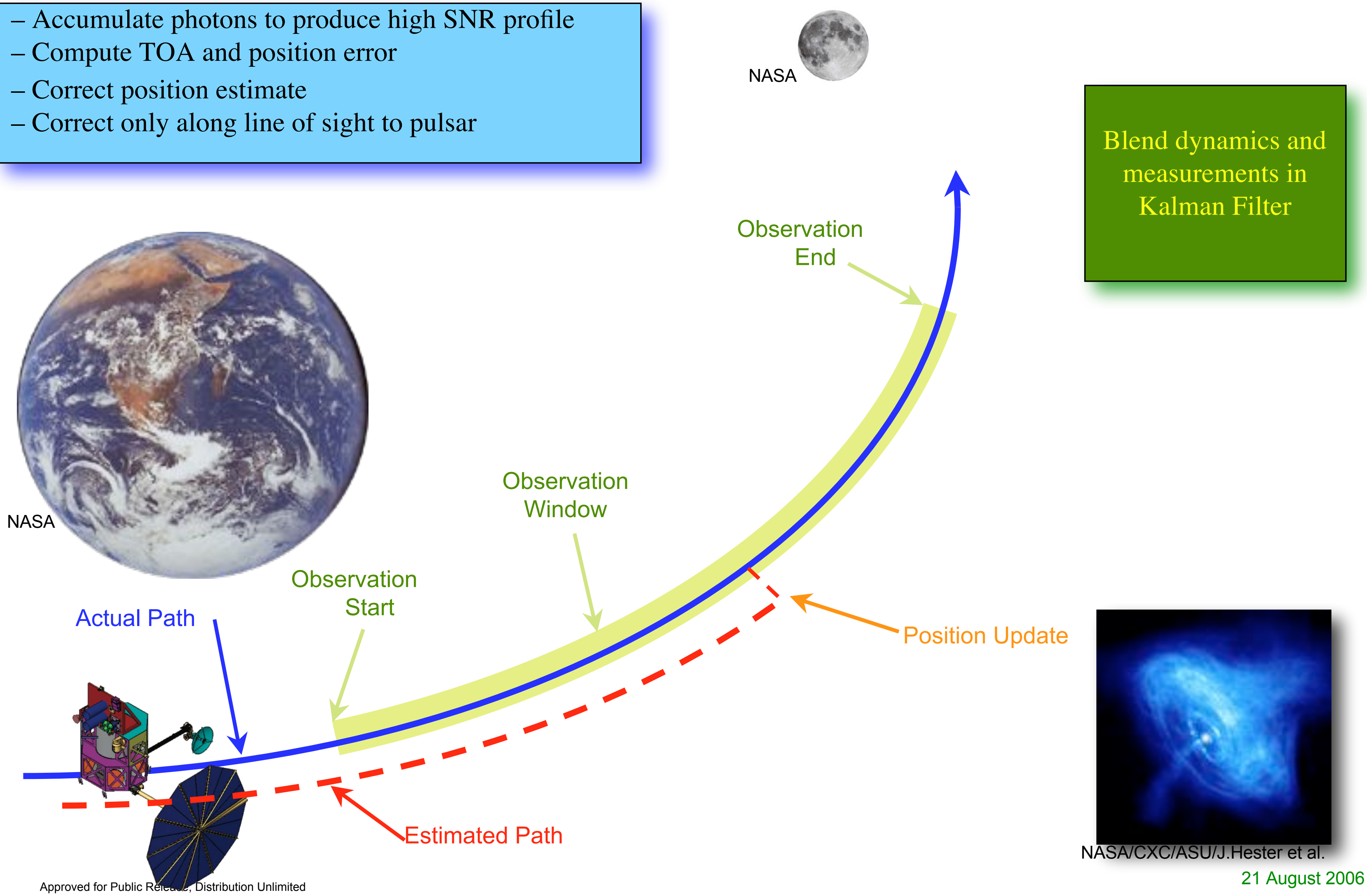
Observation Date (Dec. 1999)	Duration (s)	Observed Pulse Cycles	TOA Difference (Error) (10^{-6} s)	Position Offset (Accuracy) (km)
21^{st}	446.7	13332	53.75 (5.8)	16.1 (1.8)
24^{th}	695.9	20770	-31.02 (5.2)	-9.30 (1.6)
26^{th}	421.7	12586	-37.16 (6.3)	-11.1 (1.9)

- Truth Comparison - GPS receiver onboard *ARGOS* faulty and required correction every four hours. Actual position errors up to 15 km measured.

Position Update

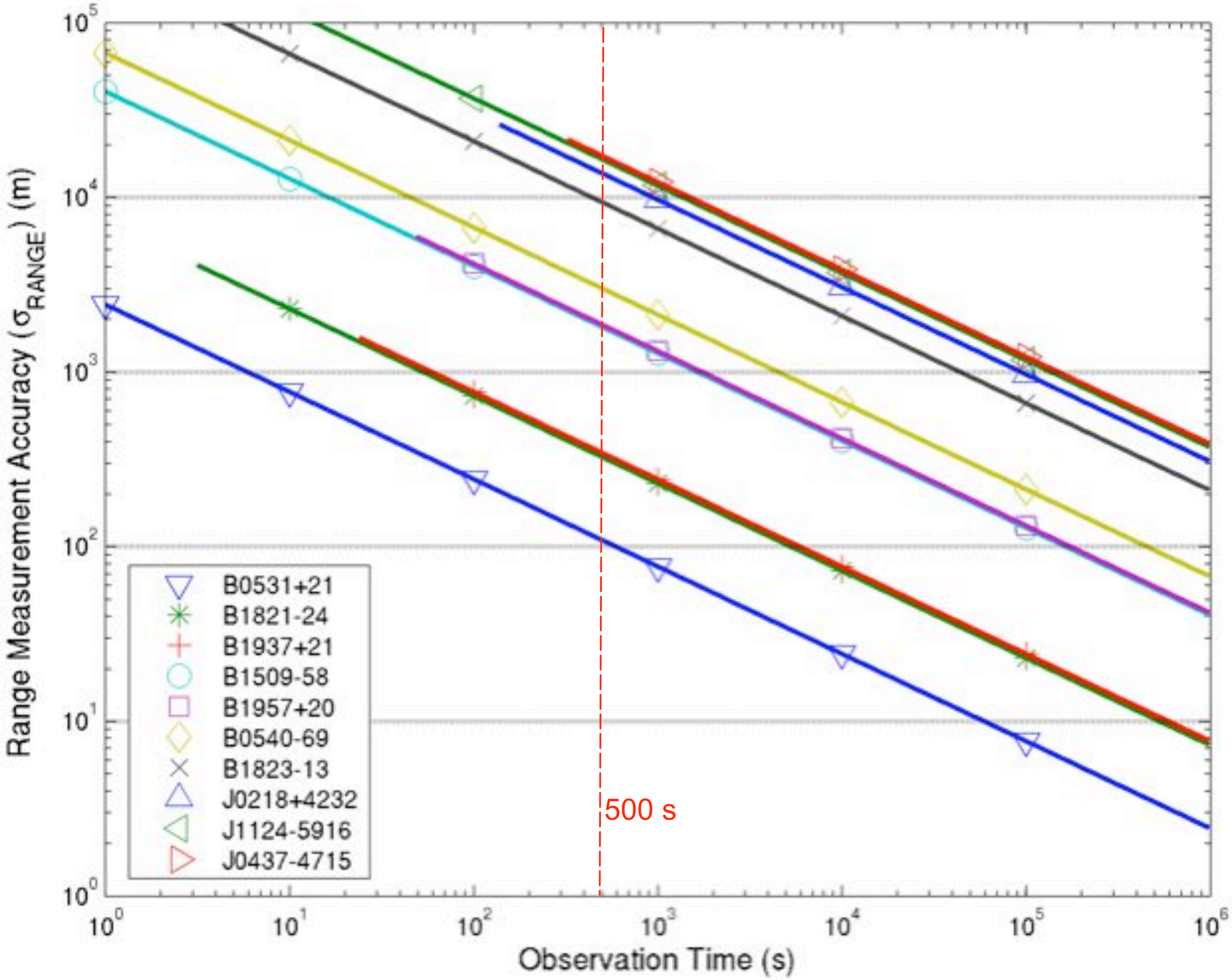
- Accumulate photons to produce high SNR profile
- Compute TOA and position error
- Correct position estimate
- Correct only along line of sight to pulsar

Blend dynamics and measurements in Kalman Filter



RPSR Range Accuracy

Estimated Range Measurement Accuracy versus Observation Time (1-m^2 Detector Area)



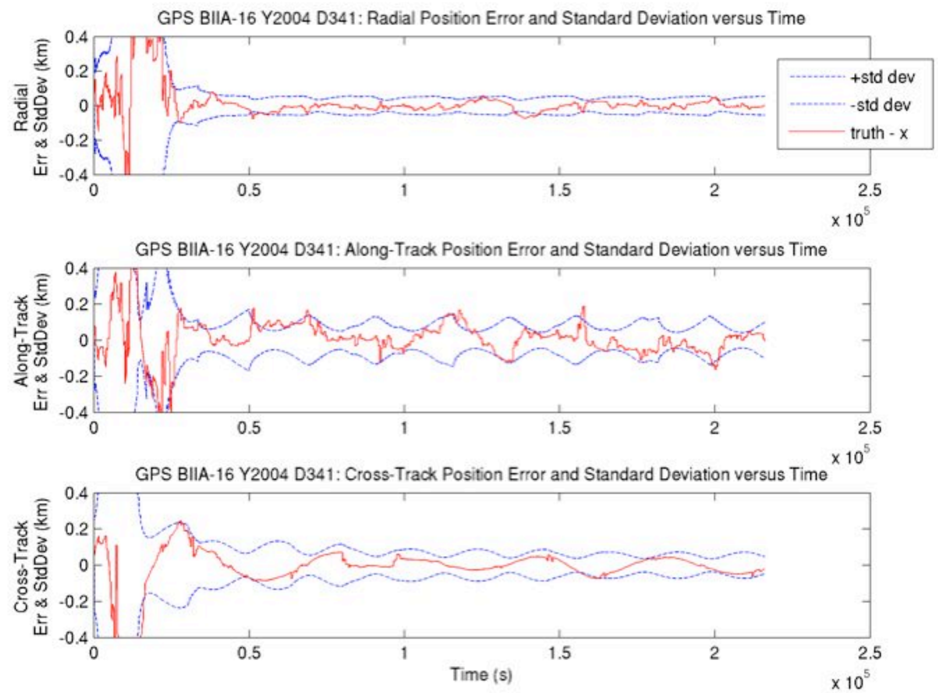
Assumes constant X-ray background = 0.005 ph/cm^2/s (2–10 keV)

- Using SNR and pulse width, compute range accuracy
- Plot shows accuracy for top 10 pulsars
  - SNR > 2
  - Assumes SNR is unlimited
- After 500 s observation:
  - B0531+21: 109 m
  - B1821-24: 325 m
  - B1937+21: 344 m

On-Orbit Navigation Simulation

- Numerical Orbit Propagator
  - Earth-system orbit
  - Perturbation acceleration effects
  - Compare to *truth* orbit solution
- Kalman filter incorporates dynamics of spacecraft
- Set initial error with respect to truth
  - Initial errors on order of 100 m and 0.01 m/s each axis
- Simulation creates pulsar-based range measurements
  - Simulate relativistic time transfer
  - Simulate noise with magnitude based on SNR plots

GPS Orbit Example



After initial filter settling, filter solution errors with respect to truth are kept below 200 m for each axis

XNAV Foreseen Benefits

- New navigation system
- Could provide full navigation solution
  - Time
  - Attitude
  - Position: < 500 m (MSRE)
  - Velocity: 10 mm/s (RMS)
- Allows autonomous vehicle operation
  - High visibility
- Backup for existing systems
  - GPS and DSN complement
- Wide operating range
  - LEO and GEO
  - Highly elliptical orbits (ex. Earth–Moon)
  - Interplanetary orbits (ex. Earth–Mars)
  - Someday ... interstellar orbits